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Finite Element Analysis of Human Tactile Sensing to Differentiate Thin Foils Through Comparison Between Vertical & Angled Loads

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Abstract

Due to increasing research demand on human tactile sensations for robot-human interfaces and new tactile sensors, this research studies human tactile sensing to differentiate the thicknesses of two extremely thin foils that are made of Cu and stainless steel (SUS). We performed finite element analysis (FEA) on the fingertip's 3D elastic model to improve previous simulations through error analyses, better selection of nodal points, and proper loading conditions. We obtained the optimum mesh size to achieve numerical error below 4%. We also compared the von Mises (VM) stress of Cu with one of the SUS foils under different loading states to monitor the t_c/t_s ratio calculated from the thicknesses of the Cu and SUS foils that cause identical VM stress. The simulated result shows that the ratio becomes considerably large when thicknesses t_c (Cu) and t_s (SUS) are calculated from the differences of the VM stress between the angular and vertical loads. Consequently, the difference between the twitch motion and the datum provides the best ratio, $t_c/t_s = 1.6$, which resembles the results of psychophysical experiments.

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Keywords: Tactile sensing; Slowly Adaptive Unit Type-1; Mechanoreceptor; Finite Element Analysis; von Mises Stress; Foil Thickness

1. Introduction

One of the latest trends in robotic design is the development of robots and devices with soft touch or compliant actuation due to the increasing developments in human-machine interfaces for rehabilitation. In general, the human

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skin provides physical protection and delicate tactile sensations. One tremendous characteristic of tactile sensations is the ability to distinguish foil thickness until several 10 μms of thicknesses when such ultra-thin thickness cannot be monitored through joint sensory organs. Since tactile sensations play a major role in this thickness discrimination process of ultra-thin foils, elucidating this mechanism is the main focus of our study.

In previous psychophysical experiments that discriminated thickness, John, Goodwin, and Darian-Smith[1] found that humans were capable of discriminating the thickness between thin material using plates from t = 200 ~ 500 μm (within a 75-μm range). One of their conclusions was that the gripping angle between fingers was the key factor that improves discrimination ability. Miyaoka and Ohka[2,3] performed a similar experiment using thinner metal foils and proposed that humans can discriminate even thinner material from t = 8 ~ 50 μm thickness, which cannot be detected by the angular sensory organs of the human finger. Consequently, one hypothesis is that evaluations for material with less than 70-μm thickness must be made using SA-I mechanoreceptor units, which exist within the structured layer of the human skin; thickness over 350 μm seems to be monitored through the joint sensory organs of fingers. Our previous simulation work[4] also highlighted the importance of the index fingers in analyzing the differences in the properties between materials. The theoretical aspects related to this experimentation can be reviewed[2~4].

The objective of this research is to study the mechanism of delicate tactile sensations and apply our findings to the development of a new robotic sensor or other human-machine interface. One extremely difficult challenge is directly monitoring the physical behavior inside our skin during contact. Past research used primates as test subjects, but current experimentation on live animals is much stricter because of the increased awareness of animal rights. Based on the above situation, we used an indirect method and performed Finite Element Analysis (FEA) on a human finger model during contact with extremely thin foils, whose copper (Cu) and stainless steel (SUS) materials were used.

The application of FEA for the behavior study of mechanoreceptors under loading was proposed by Maeno, Kobayashi and Yamazaki[5], Gerling and Thomas[6], Wu et al.[7] and others. Other research by Dandekar, Raju and Srinivasan[8] and Sripati, Bensmaia and Johnson[9] provided a good fit between the rate of the spikes fired by the Slowly Adaptive Type I (SA-I) afferent and the Strain Energy Density (SED). Lesniak and Gerling[10] focused more on the response of a single SA-I receptor by comparing the result with the psychophysics data of Phillips and Johnson[11]. Consequently, we used the FEA method instead of microneurography, which directly obtains neuron activity through a micro needle that penetrates a specific nerve fiber.

In a series of simulations, we compare the differences between the von Mises (VM) stresses generated in the skin under different loading states when the Cu and SUS foils are grasped. Since VM stress is equivalent to SED, we can estimate the tactile sensations from VM stress variations. On the other hand, we obtained the equivalent thickness of copper foil t_c to stainless steel foil t_s from a series of psychophysical experiments; ratio t_c/t_s was a constant value of around 1.5 in t_c = 30 ~ 50 μm. In this simulation, ratio t_c/t_s is defined by the thickness that causes the same VM stress. However, since ratio t_c/t_s becomes larger than 1 through simple angled or vertical loading analysis, we use the difference of the VM stresses between angular and vertical loads (treated as a datum) to calculate it. On the basis of the simulated results, ratio t_c/t_s is evaluated to obtain optimal loading for the thickness of foils using t_s as the base and the projection value of t_c (Fig. 1).

2. Procedure of FEA

2.1. Optimal Meshing

Since the main objective of this simulation is to identify the value of the VM stress inside the dermis during contact, we need to re-evaluate the previous working procedure[4] to achieve the most optimum mesh model for our simulation. We conducted error analysis of our simulated result to validate the correctness of the mesh model.

We conducted a series of simulations using CATIA V5 with a 3D elastic model of the index finger and thumb (consisting of the epidermis, dermis, bones, and nails) while grasping the Cu or SUS foil with thicknesses between t = 25 ~ 1000 μm. The main focus for this analysis identifies the specific nodal points, which represent the contact areas and the location of the SA-I mechanoreceptor unit on the fingers. An OCTREE tetrahedron mesh was applied with a revised element type from linear to quadratic to reduce the aspect ratio, especially on the foil part. The mesh size was further reduced and simplified to a 1.0-mm mesh except for 1.5-mm mesh sheets. The applied load was simplified and revised to 1.0 N for both fingers. The properties of Young's Modulus[5~7] are shown in Table 1.

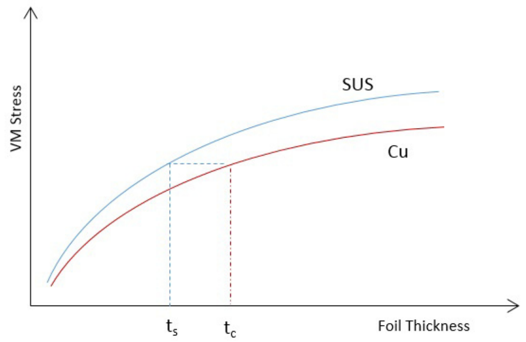

Fig. 1 Method in defining projection value of t_c for tactile ratio

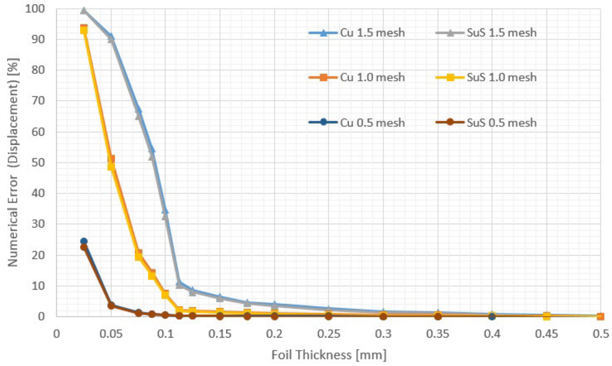

Fig. 2 Error analysis by referring to error of displacement (simulation vs. theory) using sheet model only

Table 1 Young's Modulus properties

Material Type	Young Modulus [Pa]
Epidermis/Dermis	2.0×10^{6}
Bone	1.7×10^{10}
Nail	1.6×10^{8}
SUS	2.0×10^{11}
Cu	1.1×10^{11}

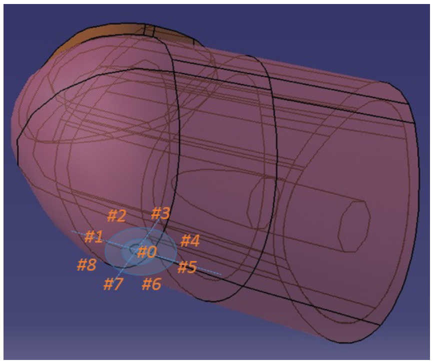

Fig. 3 New selected position and arrangement of node points

Considering that a metal foil is the most critical part (due to the high aspect ratio), the verification process uses a simple model of a clamped circular foil with the concentrated load applied to the center. The bending equation of the clamped circular plate obtained from the Theory of Plates & Shells[12] is the main reference for defining the maximum deflection. Based on the error analysis in Fig. 2, the numerical error decreases as the thickness increases. The numerical error increases abruptly under t = 0.125 mm and can be kept less than 10% with conditions where the thickness of the material is kept above t = 0.125-mm when we assume the mesh size is 1.5 mm. Due to the complicated shape of our actual finger model, we referred to this error analysis result for evaluating the actual model's behaviour. We calculated cases of $t \geq 0.2$ mm with a 1.5-mm mesh because the numerical error is within 4%. Since the case of $t = 0$ mm means direct touch between the index finger and the thumb, we focus on the calculation when the case is trusted. Between $t = 0$ and $t = 0.2$ mm, the evaluation is made using linear interpolation.

2.2. Measuring Node Points

Our next objective is to identify suitable locations for the nodal points for data extraction purposes. First, we focus on the contact points between the index finger and the foil as a base (for central nodal points) with the number of points around it to represent the behaviour of mechanoreceptor activation during loading. Based on previous findings,[4] the index finger is the main focus of this analysis. To define these contact areas, the Hertzian stress function[13] is used as the main theoretical reference. By defining the diameters of each hemisphere as 19 mm to emulate a finger, we obtain a value of $2a$ = 2.96 mm as the horizontal diameter, which is caused by two hemispheres that contact the 1-N compression. Next, we obtain a value of $2a$ = 2.39 mm from the contact analysis between single hemispheres with flat surfaces.

Valbo and Johansson[14] studied the properties of a human mechanoreceptor unit such as the size of receptive fields and the density of units. According to their report, the receptive fields of the SA-I mechanoreceptor unit consist of circular areas of around 2 ~ 5-mm diameter if a 400-μm threshold is assumed. We assumed that the numbers of mechanoreceptors within circular areas of $2a$ = 2 mm and 5 mm are $n \approx 9$ and 53 units, respectively. These values of unit numbers correspond well in our simulation. Considering the above analysis based on the mechanical contact problem and the physiology of tactile sensation, the FEA result will represent the SA-I mechanoreceptor unit's activity. In our FEA, we assume that a circular area of $2a$ = 5 mm on the fingertip is a control area to evaluate the SA-I mechanoreceptor unit's activity in the next section because the largest diameter limit seems better for the tangential force for such cases as this simulation.

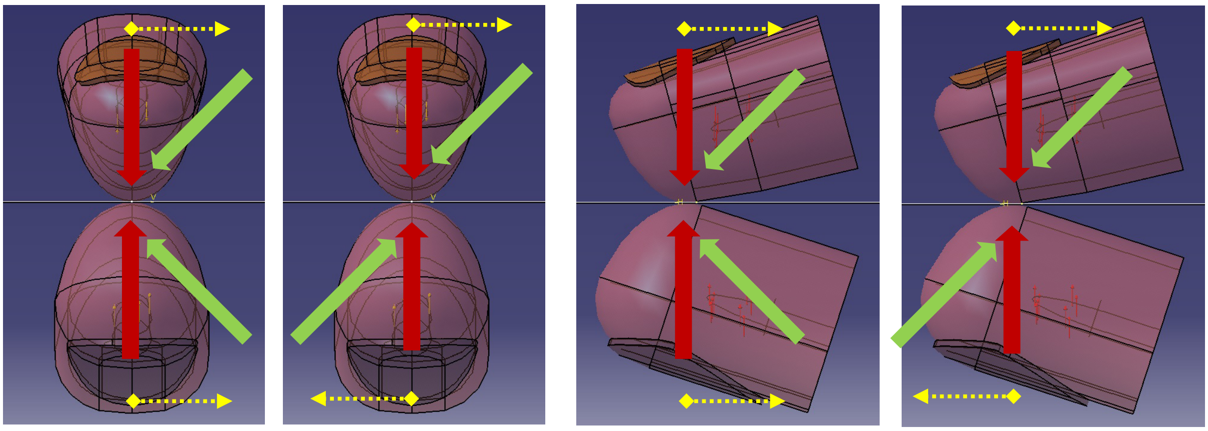

Fig. 4 Loading condition: (a) roll axis from vertical (0°) to pinch motion (15°, 30°, 45°), (b) roll axis from vertical (0°) to twitch motion (15°, 30°, 45°), (c) pitch axis from vertical (0°) to pinch motion (15°, 30°, 45°), and (d) pitch axis from vertical (0°) to twitch motion (15°, 30°, 45°). Red arrows represent vertical load, green arrows show angle load, and yellow dotted arrows show change of motion direction. Yellow dotted arrows are reversed in cases of pitch axis (opposite).

2.3. Loading Conditions

We also studied the possible behavior of both the index finger and the thumb during the evaluation process of foil thickness by handling the foils. First, we divided the behaviour into three basic conditions: the vertical loading state (datum), the angled load (pinch motion) state, and the angled load (twitch motion) state. Figs. 4(a) ~ (b) represent the loading condition within the roll axis; Figs. 4(c) ~ (d) represent the loading condition within the pitch axis. The roll axis only requires confirmation on the single phase due to a symmetrical shape, and the pitch axis requires confirmation of both the normal and opposite directions.

During the first pilot numerical experiments, we did not verify the foil thickness through the VM stress that was caused by simple loadings. This assumes that humans do not discriminate the thickness through stimulations caused by simple loading but through stimulation differences caused by motion changes. In thickness discrimination, our hypothesis is that the ability to differentiate two extremely thin materials comes from the comparison process between the vertical loading state (which is the datum) versus the angled loading state (pinch or twitch motion).

3. Simulation Results and Discussion

In this section, we discuss the simulation result using the extracted VM stress data of the index finger that interacted with the thumb and the Cu and SUS foils from the selected nodal points. The arrangement of specific nodal points are shown in Fig. 3. Instead of using their averages, we discuss the maximum VM stress values of all the selected node points. Since using average data indirectly conceals the actual activity in some areas, the maximum value represents the most significant feature. As a result, during analysis of the roll axis (pinch and twitch), the maximum VM stress occurs mostly at point #7. As for the analysis of the pitch axis (pinch and twitch), the maximum VM stress generally occurs at point #1, and for the pitch (opposite) and the twitch (opposite), it occurs more frequently at point #4.

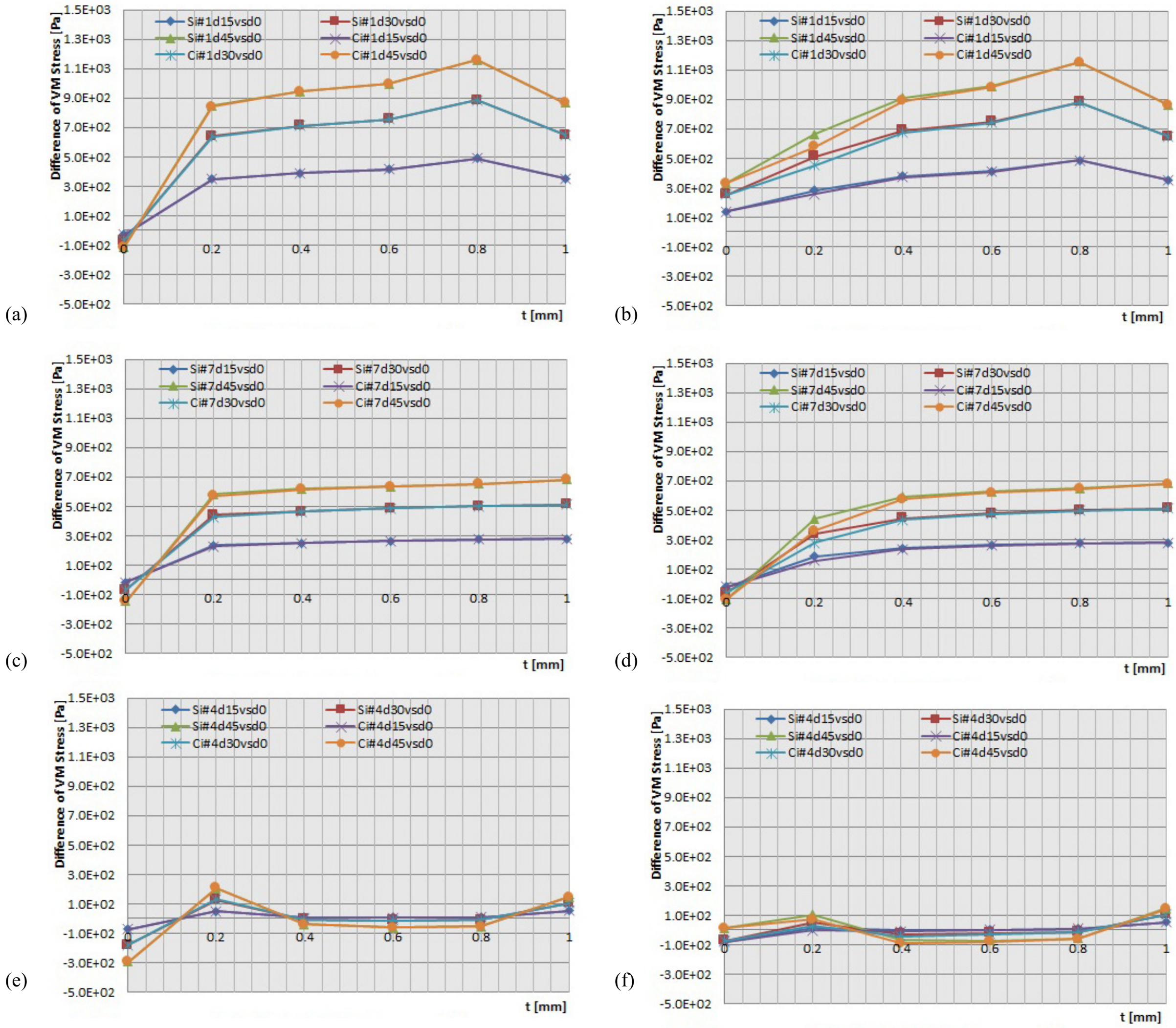

Fig 5: Comparison between differences of VM stress results of Cu and SUS material during vertical load vs angle load; based on specific node points and loading states: (a) roll axis with pinch motion, (b) roll axis with twitch motion, (c) pitch axis with pinch motion, (d) pitch axis with twitch motion, (e) pitch axis with pinch (opposite) motion, and (f) pitch axis with twitch (opposite) motion.

First, we examined all the simulation results and plotted them as a relationship between VM stress and foil thickness. In these graphs, almost all the curves decreased with an increase of thickness, where the SUS foil shows higher VM stress than the Cu foil in each case. Since this means that identical VM stress (SA-I mechanoreceptor unit activation) causes larger SUS foil thickness than the Cu foil, the single loading condition is not used to evaluate foil thickness. Consequently, we assumed that humans judge the foil thickness by the difference in the VM stress caused in the dermis. This assumption is naturally accepted because in daily life we sometimes pinch sheets between two fingers and slide our fingers on them.

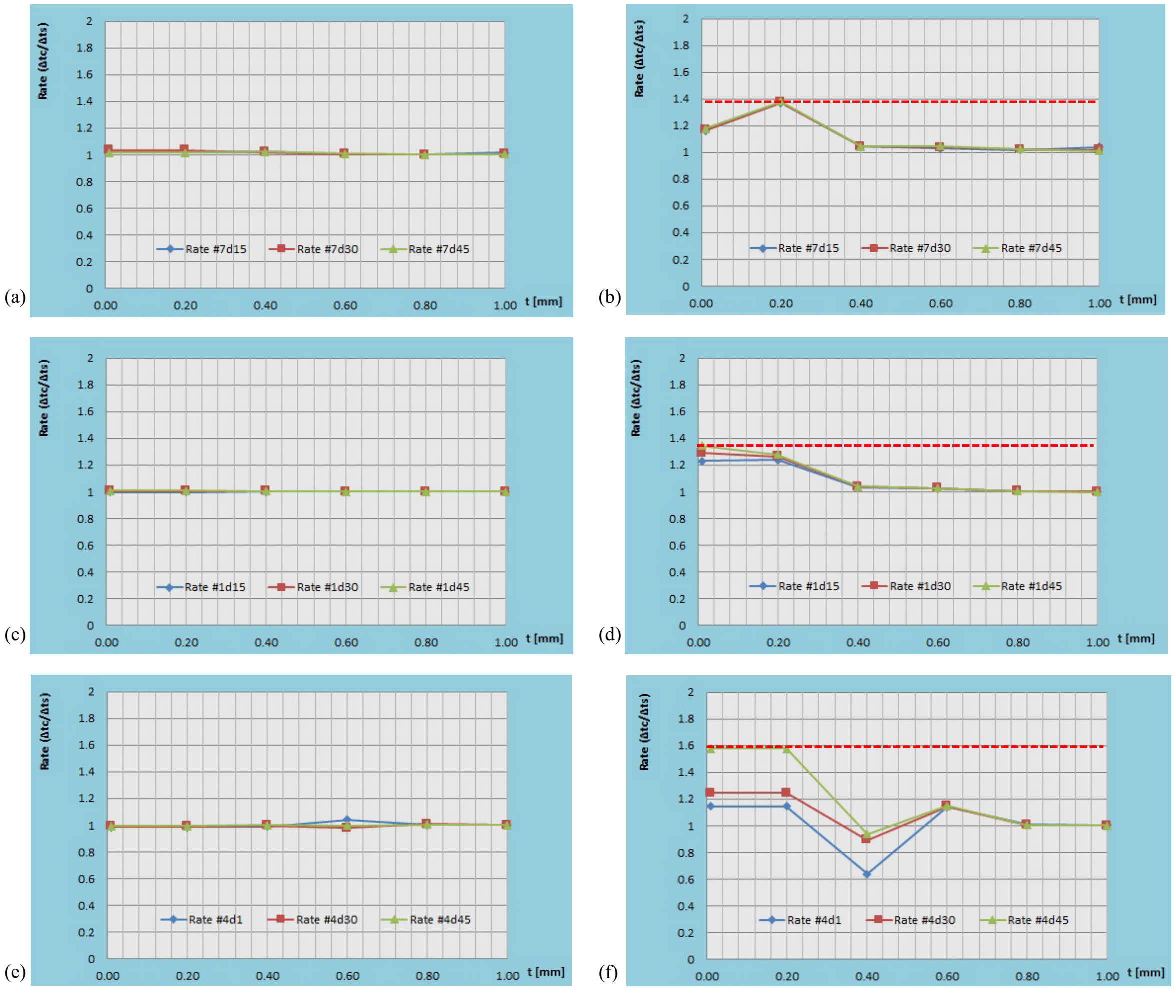

Fig. 6 t_c/t_s ratio (with reference to average VM stress of Cu and SUS) based on specific node points and loading states: (a) roll axis with pinch motion, (b) roll axis with twitch motion, (c) pitch axis with pinch motion, (d) pitch axis with twitch motion, (e) pitch axis with pinch (opposite) motion, and (f) pitch axis with twitch (opposite) motion.

Figure 5 shows the relationship between the differences of the VM stress on the vertical vs. angled load for both the SUS and Cu foils. These results show that the ability to differentiate between thicknesses by the difference of VM stress is more obvious when the comparison is made between twitch motion loads vs. direct load (datum). From a majority of the results, the differences between both the Cu and SUS materials are more observable, especially during twitch motions.

Next, by referring to Fig. 6, the differences of the t_c/t_s ratio are also more noticeable depending on the difference of the loading motion. In the determination of t_c and t_s, we obtain graphs whose ordinate is the difference between the VM stresses of the angled load vs. the datum, the abscissa is the thickness, and t_c and t_s are estimated as the thickness that causes the same magnitude of the differences between the VM stresses in the graphs (Fig. 1). Especially in Fig. 6(f), by comparing the ratios during a twitch motion of a 45° angle load with a datum, a maximum

t_c/t_s = 1.6 ratio was achieved. If we compare this with the ratios of previous psychophysics experimentations[2, 3], which were around 1.5, the present result provides almost identical value.

4. Conclusion

To elucidate the mechanism of foil thickness recognition, we conducted an FEA analysis using a 3D model of an index finger, a thumb, and various sheet metals as a base. We achieved our main objective, which was to identify the VM stress value within the epidermis section. We managed to maintain the simulation's convergence rate by optimum use of the mesh size and to keep the numerical error below 4% during the simulation. Based on the simulation results, we monitored the basic behaviour of the human tactile mechanism to define the differences between two extremely thin foils. This simulation result also supports our initial hypothesis in which SA-I mechanoreceptor units play the main role in defining the differences between the foils. In the future, we will expand the findings of this paper to the experimental procedures of robotic tactile sensing using a three-axis tactile sensor[15]. With a robotic hand equipped with three-axis tactile sensors, we will evaluate the present loading manner to increase the precision of the foil thickness discrimination. We expect that continuing FEA to evaluate mechanoreceptor unit's activation will be embraced to deepen our understanding of the human tactile mechanism.

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References

1. John, K. T., A. W. Goodwin, and I. Darian-Smith. "Tactile discrimination of thickness." *Experimental brain research* 78, no. 1 (1989): 62-68.
2. T. Miyaoka and M. Ohka. "Tactile information processing mechanisms to discriminate foil thickness." *Proceedings of the Seventeenth Annual Meeting of the International Society for Psychophysics*. Vol. 17. (2001)
3. T. Miyaoka and M. Ohka. "The Duplex Theory of thickness discriminations by touch," *JSME annual meeting* 2002(1), 231-232.
4. Jusoh, M. A. M., M. Ohka, and Y. C. Wang. "Finite Element Analysis on the Mechanism of Human Tactile Sensation in Comparing Different Material Properties and Thickness." *Applied Mechanics and Materials* 393 (2013): 617-622.
5. T. Maeno, K. Kobayashi, and N. Yamazaki. "Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors." *JSME International Journal Series* C 41, no. 1 (1998): 94-100.
6. G. J. Gerling and G. W. Thomas. "Fingerprint lines may not directly affect SA-I mechanoreceptor response." *Somatosensory & motor research* 25, no. 1 (2008): 61-76.
7. Wu, John Z., Daniel E. Welcome, and Ren G. Dong. "Three-dimensional finite element simulations of the mechanical response of the fingertip to static and dynamic compressions." *Computer methods in biomechanics and biomedical engineering* 9, no. 1 (2006): 55-63.
8. K. Dandekar, I. R. Balasundar, and M A. Srinivasan. "3-D finite-element models of human and monkey fingertips to investigate the mechanics of tactile sense." *Journal of biomechanical engineering* 125, no. 5 (2003): 682-691.
9. A. P. Sripati, Sliman J. Bensmaia, and Kenneth O. Johnson. "A continuum mechanical model of mechanoreceptive afferent responses to indented spatial patterns." *Journal of neurophysiology* 95, no. 6 (2006): 3852-3864.
10. D. R. Lesniak and G. J. Gerling. "Predicting SA-I mechanoreceptor spike times with a skin-neuron model." *Mathematical biosciences* 220, no. 1 (2009): 15-23.
11. Johnson, Kenneth O. and John R. Phillips. "Tactile spatial resolution. I. Two-point discrimination, gap detection, grating resolution, and letter recognition." *Journal of Neurophysiology* 46, no. 6 (1981): 1177-1192.
12. S. Timoshenko and SW Krieger. *Theory of plates and shells*. Vol. 2. New York: McGraw-hill, 1959.
13. S. Timoshenko. "*Strength of Materials (Part 2) Advanced Theory and Problems.*" 2nd Ed. D. Van Nos-trand Company, 1940: 339~360.
14. R. S. Johansson and Åke B. Vallbo. "Tactile sensory coding in the glabrous skin of the human hand." *Trends in neurosciences* 6 (1983): 27-32.
15. M. Ohka, H. Kobayashi, J. Takata, and Y. Mitsuya. "Sensing precision of an optical three-axis tactile sensor for a robotic finger." *In Robot and Human Interactive Communication*, 2006. ROMAN 2006. The 15th IEEE International Symposium on, pp. 214-219. IEEE, 2006.